COMPUTER SIMULATON OF THE UMER GRIDDED GUN*

I. Haber, S. Bernal, R. A. Kishek, P. G. O'Shea, M. Reiser, Y. Zou+, University of Maryland College Park, MD, U.S.A.

A. Friedman, D. P. Grote, J. -L. Vay, LBNL, Berkeley, CA, U.S.A.

Abstract

The electron source in the University of Maryland Electron Ring (UMER) injector employs a grid 0.15 mm from the cathode to control the current waveform. Under nominal operating conditions, the grid voltage during the current pulse is sufficiently positive relative to the cathode potential to form a virtual cathode downstream of the grid. Three-dimensional computer simulations have been performed that use the mesh refinement capability of the WARP particle-in-cell code to examine a small region near the beam center in order to illustrate some of the complexity that can result from such a gridded structure. These simulations have been found to reproduce the hollowed velocity space that is observed experimentally. The simulations also predict a complicated time-dependent response to the waveform applied to the grid during the current turn-on. This complex temporal behavior appears to result from the dynamics of the virtual cathode formation and may therefore be representative of the expected behavior in other sources, such as some photoinjectors, that are characterized by a rapid turnon of the beam current.

INTRODUCTION

UMER was designed to study propagation of a highly space-charge-dominated beam over a long path length. The fundamentally nonlinear characteristics of such an intense beam have generally mandated the use of numerical simulation for understanding the propagation characteristics.

It has been observed that the dominant nonlinear physics during propagation of a beam as intense as the one in UMER is sensitive to the details of the initial beam distribution function. Propagation characteristics of the beam also can depend on internal correlations in the beam distribution that are difficult to measure directly, necessitating a reliance on simulation. In performing simulations of the initial distribution, it is conceptually advantageous to examine the beam starting from the emitter surface. When the beam is born, the correlations in the beam distribution function are thought to be relatively simple. It is then possible to follow the beam evolution and examine the mechanisms by which internal correlations are established. The beam characteristics can then be benchmarked against any experimental data that can be obtained.

Though such "first principle" simulation of the electron gun in UMER is conceptually attractive, the actual calculations are not straightforward. This occurs because in order to control of the beam current waveform, the electron gun in UMER employs a fine rectangular grid, similar in pattern in a window screen, that is placed close to the cathode. This results in disparate spatial scales that range from the 0.0254 mm diameter of the grid wires that are 0.15 mm from the cathode and 0.15 mm apart, to the approximately 25 mm distance between the cathode and the anode.

STEADY STATE SIMULATIONS

During commissioning of the UMER injector preliminary measurements of the beam emerging from the UMER gun were obtained using a pepper pot in combination with a phosphor screen mounted on a stalk that could be moved to close proximity to the gun anode. An unexpectedly complex beam distribution was observed whose most notable feature was hollowing in the velocity-space distribution. Also observed during these early measurements was a complex transverse variation in the current density.

Simulations employing the WARP electrostatic P.I.C. code[1] that inject a beam at the cathode plane with a velocity distribution approximating the actually-measured hollow velocity distribution were somewhat successful in reproducing the complex transverse current variation that was observed.[2] This assumption of an initial hollow velocity distribution emerging from the gun also improved agreement with the observed transverse current variation further downstream.[3] Simulations to understand the mechanism responsible for the initial hollow velocity space distribution were then undertaken.

SIMULATION OF THE CATHODE GRID

While many computer codes have been written to simulate electron gun physics, the proper inclusion of transient behavior is still not straightforward because the transient behavior can be dominated by the details of the self-consistent space-charge forces in the immediate vicinity of the emitting surface. Simulations using the mesh refinement capability of the WARP code have demonstrated the importance of using a refined mesh to reproduce the steep gradients in current variation in the emitter region.[4] The detailed accurate agreement between the predictions of this code and experimental measurement on the Source Test Stand ion diode[5] has also strongly supported the importance of using mesh refinement and the credibility of the WARP implementation.

*Work supported by U. S. Department of Energy

+ Present address: GE Global Research, Niskayuna, NY 12309, USA

Operation of the UMER gridded gun is thought to be inherently complex. A theoretical analysis of the operation of such a gridded gun [6] has predicted that, in the usual operating, the gun current is limited by a virtual cathode formed downstream of the grid. The hollowing in velocity space appears to result from the details of the cathode-grid structure as it interacts with this virtual cathode. In addition, a second possible virtual cathode can be formed in close proximity to the cathode and can also influence the gun characteristics by affecting the current that reaches the cathode grid.

It is therefore evident that in order to reliably represent the UMER gun behavior, it is necessary to adequately resolve not only the grid geometry, but also the two regions that can form virtual cathodes downstream of the cathode and of the cathode grid. In the case of the cathode grid, simple simulations were used to determine that numerical convergence could be obtained with a longitudinal mesh separation of approximately a few microns. Unequal mesh sizes are clearly required to simultaneously resolve this distance at the same time as spanning the cathode to anode distance of approximately 0.025m.

Rather than assume a Child-Langmuir model for the cathode emission, as is commonly employed in gun codes, it was decided to simply emit particles from the cathode surface, with a Gaussian velocity distribution, in sufficient number to represent several times the expected Child-Langmuir limit. To simplify the numerics a thermal spread was assumed that is approximately twice that corresponding to the approximately 0.1 eV cathode temperature. A virtual cathode is then allowed to form self-consistently. Because of the difficulty of resolving the large number of grid wires in the transverse region, only a single cell of the gridded structure was simulated. Periodic boundaries were assumed so that the geometry approximates the rectangular region represented by a single 0.15 mm square grid cell in the center of the gun structure. In addition, fourfold transverse symmetry was assumed to reduce the computational requirements.

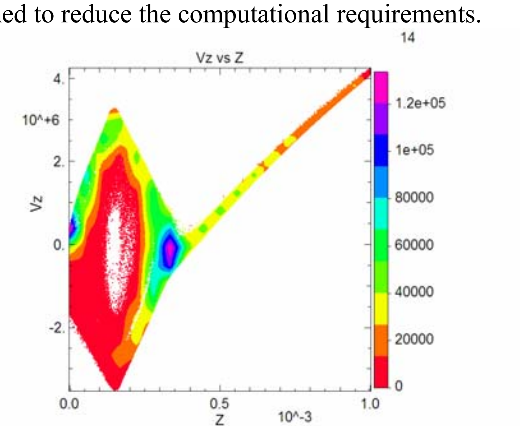

Figure 1. z-vz space showing the structure of virtual cathode downstream of the cathode grid.

A virtual cathode downstream of the grid was observed as predicted[6] and a hollow velocity distribution similar to what was seen experimentally also developed.[7] Figure 1 is a z-vz phase space plot of a typically observed virtual cathode. In addition to the expected virtual cathode formation however, a complex temporal behavior that persisted for several ns, was also observed in these simulations, as shown by the plot in Fig. 2 of the time history of the current slightly downstream from the virtual cathode. The mechanism for this complex behavior is believed to be similar to what is predicted by Valfells et al. [8] That is, as the current increases in the region downstream of the grid, the potential drop that causes the virtual cathode also chokes off the current necessary for the that potential drop to be maintained. This causes a transient increase in the current that leads to the reestablishment of the virtual cathode. The variation in virtual cathode is accompanied by a corresponding variation in the transverse velocity distribution, with the degree of hollowing correlating to the strength of the virtual cathode.

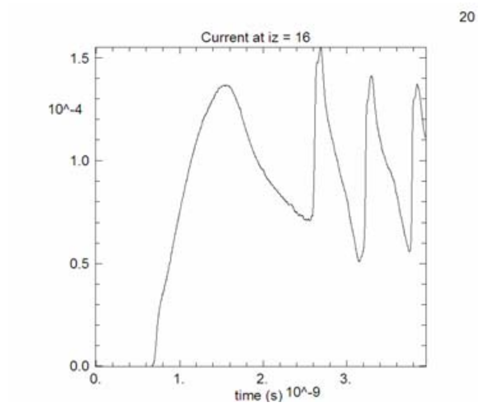

Figure 2. Temporal behavior of the beam current at z=1.5mm from the cathode. The grid-to cathode potential of 30V is turned on over a 2 ns period. The grid to anode potential is 10 KV.

It is important to emphasize that the details predicted by these simulations of the temporal behavior are considered preliminary, despite the substantial number of numerical tests that have been performed. While it is easy to postulate such transients in the beam behavior, because of the complexity of the geometry there is still some uncertainty in the accuracy of the numerics. For example, the two regions, upstream and downstream of the grid, are coupled by particles that are reflected by the virtual cathode downstream of the grid. These particles enter the region upstream of the grid, suppressing the potential and possibly the current between the grid and cathode. The numerical requirements for simulating the behavior of counterstreaming beams in this region has not yet been adequately investigated. Also complicating determination of the fidelity of the simulations by comparing to experiments is the difficulty in conducting direct measurement of the time-dependent cathode-to-grid potential, which because of the loading on the grid supply could deviate substantially from the constant potential assumed. It is also difficult to measure transient behavior at the high frequencies predicted by the simulations, especially since the simulations predict that the temporal

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fluctuations are substantially reduced by longitudinal space charge as the beam propagates into the downstream region where it could be measured.

"SEMI-TRANSPARENT" SURFACE

The simulations of a small region in the center of the beam do not properly model the transverse beam evolution. For example, the beam radius is kept constant; therefore the evolution in beam radius that occurs as the beam propagates from cathode to anode is neglected. When the beam current is modulated in time as observed in the simulations, the change in beam current often results in a corresponding change in beam radius and this temporal change in the beam radius may affect the transient behavior. In view of the difficulty of actually resolving the transverse grid structure, one approximation that can be employed is to replace the grid with an equipotential surface at the grid potential that absorbs a percentage of the beam. The percentage of the beam absorbed was fixed at the ratio of the transverse area occupied by the wires (69%) and this absorption is applied to particles traveling in both directions.

An intermediate step was performed relating the beam evolution including the detailed model of the wires to the evolution with a semi-transparent surface in the same small central region with periodic boundary transverse boundary conditions. The behavior in these two cases is not identical, but the basic features of the current waveform are quite similar.

In view of the similarities of the semi-transparent grid simulations to the simulations with those that incorporate the detailed grid wire model, r-z simulations of the full gun have been performed. These simulations are subject to the same caveats appropriate to the three-dimensional simulations of the influence of the grid structure. In fact, since the computational requirements of these simulations, performed assuming axisymmetry are not as severe as the three-dimensional cases, several runs have been performed that give further insight into the complexity that is possible in the two coupled regions. On interesting observation results from the necessity to choose the value of the total current injected at the cathode surface. Because of the observed time dependence of the current reaching the grid, injecting more current can actually reduce the average current transmitted past the virtual cathode. This observed deviation from a monotonic relation between injected and transmitted current is a possible explanation for the observed maximum that is observed in gun current, as the cathode temperature is increased.

CONCLUSIONS

Preliminary simulations have been performed to aid in understanding the observed complexity of the UMER gridded gun. Emphasis thus far has been on establishing the requirements for numerical convergence. Emphasis will be shifted to exploring the range parameter space in actual operation in order to seek measurable consequences of the numerical predictions. Because of the difficulty in conducting measurements in the immediate vicinity of the gun and the space charge to smoothing in current variation as the beam propagates, direct comparison of simulated behavior to experiment in the near term may be difficult. However, some indirect implications, such as the observed peak in the output current as a function of heater temperature can be investigated.

On a longer-term basis, laser stimulation of the cathode emission as well as optical transition radiation measurements of the beam characteristics on a fast time scale might be used to examine the implications of the predicted short-time-scale behavior. Also possible is benchmarking the code on a gun structure less complex than the UMER gun, or examination of short-time-scale photocathode behavior to establish the relevance of transient behavior in the virtual cathode region to beam characteristics.

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